ACTA GEOGRAPHICA SLOVENICA

GEOGRAFSKI ZBORNIK



2026
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ACTA GEOGRAPHICA SLOVENICA
GEOGRAFSKI ZBORNIK
66-1 • 2026

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ISSN 1581-6613

ACTA GEOGRAPHICA SLOVENICA

66-1
2026

ISSN: 1581-6613 (*Print edition/tiskana izdaja*)
ISSN: 1581-8314 (*Online edition/spletna izdaja*)
UDC: 91
2026, ZRC SAZU, Geografski inštitut Antona Melika

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Issued by/izdajatelj: Geografski inštitut Antona Melika ZRC SAZU
Published by/založnik: Založba ZRC
Co-published by/sozaložnik: Slovenska akademija znanosti in umetnosti

Address/naslov: Geografski inštitut Antona Melika ZRC SAZU, Gosposka ulica 13, p. p. 306, SI – 1000 Ljubljana, Slovenija; ags@zrc-sazu.si

The articles are available on-line/prispevki so dostopni na medmrežju: http://ags.zrc-sazu.si
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Ordering/naročanje: Založba ZRC, Novi trg 2, p. p. 306, SI – 1001 Ljubljana, Slovenija; zalozba@zrc-sazu.si

Annual subscription/letna naročnina: 20 €
Single issue/cena posamezne številke: 12 €

Cartography/kartografija: Geografski inštitut Antona Melika ZRC SAZU
Translations/prevodi: DEKS, d. o. o., Živa Malovrh
DTP/prelom: SYNCOMP, d. o. o.
Printed by/tiskarna: CICERO, Begunje, d. o. o.
Print run/naklada: 250 copies/izvodov

The journal is subsidized by the Slovenian Research and Innovation Agency (B6-7614) and is issued in the framework of the Geography of Slovenia core research programme (P6-0101)/Revija izhaja s podporo Javne agencije za znanstvenoraziskovalno in inovacijsko dejavnost Republike Slovenije (B6-7614) in nastaja v okviru raziskovalnega programa Geografija Slovenije (P6-0101).

The journal is indexed also in/revija je vključena tudi v: Clarivate Web of Science (SCIE – Science Citation Index Expanded; JCR – Journal Citation Report/Science Edition), Scopus, ERIH PLUS, GEOBASE Journals, Current geographical publications, EBSCOhost, Georef, FRANCIS, SJR (SCImago Journal & Country Rank), OCLC WorldCat, Google Scholar, CrossRef, and DOAJ.

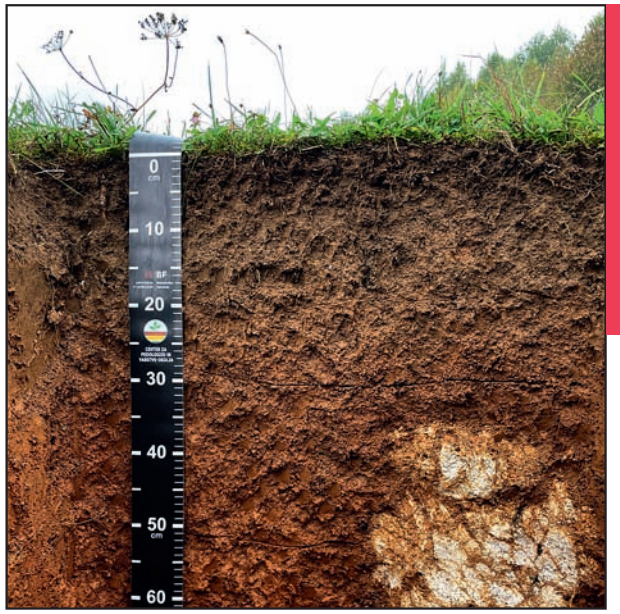
Design by/Oblikovanje: Matjaž Vipotnik

Front cover photography: Sečovlje Salt Pans at the Slovenian coast (photograph: SeanPavonePhoto, stock.adobe.com).
Fotografija na naslovnici: Sečoveljske soline na slovenski obali (fotografija: SeanPavonePhoto, stock.adobe.com).

Acta geographica Slovenica, 66-1, 2026, 21–38

SOILS OF THE DINARIC KARST IN SLOVENIA: PROPERTIES, PEDOGENESIS AND LAND USE

Rok Turniški, Helena Grčman



ROK TURNIŠKI

Luvisol developed over dolomite.

DOI: https://doi.org/10.3986/AGS.14434
UDC: 631.41:552.54(497.4-13)
332.362:631.4(497.4-13)
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Rok Turniški[1], Helena Grčman[1]

Soils of the Dinaric karst in Slovenia: properties, pedogenesis and land use

ABSTRACT: The study evaluates the physical and chemical properties of soils developed on limestones and dolomites in the Dinaric karst of Slovenia. Statistical analysis of 257 soil profiles was performed to compare the properties of different soil types and to assess the impact of land use on soil characteristics. The predominant soil types in the area are Leptosols and Phaeozems, followed by Eutric Cambisols and Luvisols. Although these soils are chemically fertile, their agricultural potential is limited due to their variable depth, rocky surface, and lack of surface water. As a result, forests are the predominant type of land use. Land use influences soil processes and properties, as evidenced by the differences in soil pH, base saturation, cation exchange capacity and organic matter content.

KEYWORDS: soil, karst, carbonate parent material, Leptosols, Phaeozems, Cambisols, Luvisols

Tla dinarskega krasa Slovenije: lastnosti, pedogeneza in raba tal

POVZETEK: V raziskavi predstavljamo pregled fizikalnih in kemijskih lastnosti tal (prsti) na apnencih in dolomitih dinarskega krasa v Sloveniji. Izvedli smo statistično analizo 257 talnih profilov. Primerjali smo lastnosti glavnih talnih sistematskih enot in vrednotili vpliv rabe tal. Prevladujoča talna sistematska enota so rendzine, sledijo rjava pokarbonatna tla in izprana tla. Kljub ugodnim kemijskim lastnostim, ki kažejo na visoko rodovitnost, je njihova kmetijska raba omejena zaradi različne globine, površinske skalovitosti in pomanjkanja površinske vode. Zaradi teh omejitev je prevladujoča vrsta rabe tal na dinarskem krasu gozd. Raba tal vpliva na procese in lastnosti tal, kar se odraža v razlikah v pH, nasičenosti z bazičnimi kationi, kationski izmenjalni kapaciteti in vsebnosti organske snovi.

KLJUČNE BESEDE: tla/prst, kras, karbonatna matična podlaga, Leptosols, Phaeozems, Cambisols, Luvisols

The article was submitted for publication on April 25th, 2025.
Uredništvo je prejelo prispevek 25. aprila 2025.

[1] University of Ljubljana, Biotechnical Faculty, Ljubljana, Slovenia

rok.turniski@bf.uni–lj.si (https://orcid.org/0000–0002–0630–6620), helena.grcman@bf.uni–lj.si (https://orcid.org/0000–0003–0724–9151)

1 Introduction

The Dinaric karst region (Figure 1) covers almost one fifth of the territory of Slovenia (Zorn et al. 2020). It consists mainly of Triassic, Jurassic and Cretaceous limestones and dolomites (also named dolostones) (Dozet and Pleničar 2009; Knez and Kranjc 2009), which are considered very pure and contain only a small proportion of insoluble residues (Ogorelec and Rothe 1992; Pleničar and Dozet 1993; Gams 2004). The area is characterised by plateaus with intervening depressions and lowlands in which the karst poljes extend (Knez and Kranjc 2009). The pedogenesis of soils on limestone and dolomite, their productivity and land use have been studied since the middle of the 20th century. Early research on the Terra rossa of the Karst Plateau (SW Slovenia) by Sušin (1964) in the 1960s, for example, contributed significantly to the knowledge of soil properties associated with limestone bedrock. Meanwhile, Gregorič's (1965) doctoral thesis on soil genesis on the dolomites of the Dolenjska region attempted to clarify the origin of the reddish-brown Bt horizons and two-layer soil profiles. Sušin (1972) investigated the differentiation of clay content and colour variability in relation to pedogenesis. At the time, Lobnik (1978) studied the migration of manganese and the formation of manganese concretions and coatings on structural aggregates in Eutric Cambisols on dolomite. Overall, the soil research conducted supported the theory of polygenetic soil formation on carbonate bedrock (Gregorič 1965; Sušin 1972), which is widely accepted today (Costantini et al. 2018; Durn et al. 2023). As the exact pathways of formation remain a hotly debated topic, research into soil formation and development in karst environments remains relevant. This is demonstrated, for instance, by a recent study on the Divača karst (Zupančič et al. 2018), which highlighted the geochemical fingerprint of insoluble material in soils on different limestone formations and drew particular attention to other materials contributing to soil mass, including interbedded material, palaeosoils, and probably aeolian material. Improved analytical methods in the fields of geochemistry, minerals and micromorphology have recently triggered a new wave of soil research across the Dinaric karst region (Durn et al. 2021; Durn et al. 2023; Turniški et al. 2023). In the 1970s, soil scientists and agronomists began to investigate the productive potential of karst soils. Having identified their properties and spatial distribution, they evaluated the most suitable types of land use. Since the shallow depth and rocky nature of karst soils hindered ploughing, they emphasised the importance of these soils for livestock production, and, consequently, for protein supply, which was a major concern at the time. Stepančič (1972) also compared soils developed on limestone and dolomite. He concluded that soils on limestone were mainly covered by forest due to the rocky and cavernous relief associated with this type of bedrock. The rock-free surfaces of soils on dolomite, on the other hand, made them more suitable for agriculture. At the same time, Stritar (1972) focused on the land use of rendzinas formed on dolomite, while Ažnik (1975) studied their productive potential. Eutric Cambisols (slv. *rjava pokarbonatna tla*) on dolomite in the Lower Carniola (slv. *Dolenjska*) were studied by Stepančič (1972), and on the Karst Plateau (slv. *Kras*), the suitability of Terra rossa for viticulture was examined by Stepančič and Ažnik (1976). Stritar (1967) also investigated the agricultural value of soils associated with a specific forest type (slv. *steljnik*) consisting of silver birch (*Betula pendula*), common heather (*Calluna vulgaris*) and eagle fern (*Pteridium aquilinum*), which frequently occurs on the Luvisols (slv. *izprana tla*) of the White Carniola (slv. *Bela krajina*) in SE Slovenia. The most systematic and extensive soil survey was carried out between 1960 and 1990 to produce the Slovenian soil map at a 1:25,000 scale (Vidic et al. 2015).

Previous studies have focused on geographically narrower areas, whereas the aim of our research was to analyse the spatial distribution of soil types developed on limestone and dolomite in the Dinaric karst region, based on the comprehensive database of the digital soil map of Slovenia, and to provide an overview of their chemical and physical properties in relation to pedogenetic processes and human influences. Particular attention was paid to analysing soil properties that are important for agricultural use and to identifying significant differences between forest and agricultural topsoils that can be attributed to human activities.

2 Materials and methods

2.1 Study area

The study area covered the Dinaric karst of Slovenia (Figure 1), which is bounded in the north by the Julian Alps, the Lower Carniola Lowland (slv. *Dolenjsko podolje*), and the Sava River (Mihevc and Prelovšek 2010).

The predominant part of the Dinaric karst in Slovenia is influenced by a temperate continental climate with average annual precipitation ranging from 1300 to 2800 mm and average temperatures of the coldest month ranging from 0 to –3°C and of the warmest month from 15 to 20°C (Ogrin 1996). White Carniola is distinguished by lower average annual precipitation, ranging between 1200 and 1300 mm. The Mount Snežnik area is characterised by a low average temperature in the coldest month (below –3°C) and high annual precipitation ranging between 1600 and 3000 mm. In contrast, the Karst Plateau is characterised by generally higher temperatures, with the average temperature in the coldest month above 0°C and in the warmest month above 20°C, and average annual precipitation ranging between 1200 and 1700 mm (Ogrin 1996).

2.2 Source of data and analysis

The study is based on data from the Soil Map of Slovenia 1:25,000 (PK25) available from Soil Information System of the Infrastructure Centre for Soil and Environmental Sciences (TIS-ICPVO) provided by Biotechnical Faculty, University of Ljubljana (Infrastrukturni … 2023). The physical and chemical properties (Table 1) of the soils were analysed in the ICPVO laboratory following the standardised protocols described in Vidic et al. (2015). For the area of the Dinaric karst in Slovenia (Zorn et al. 2020), the pedocartographic units (PCUs) were exported from the PK25 attribute table and merged into a new data layer. The physical and chemical properties of 747 individual soil horizons from 257 soil profiles within the study area (Figure 1) were statistically evaluated using descriptive statistics to characterise the central tendency and variation of soil properties. Data processing was carried out using the statistical computing environment R v.4.2.3 (R Foundation … 2023). The package »aqp« (Beaudette et al. 2013) was used to plot the soil depth functions and »ggplot2« (Wickham 2016) was used to generate the texture triangles and mean plots.

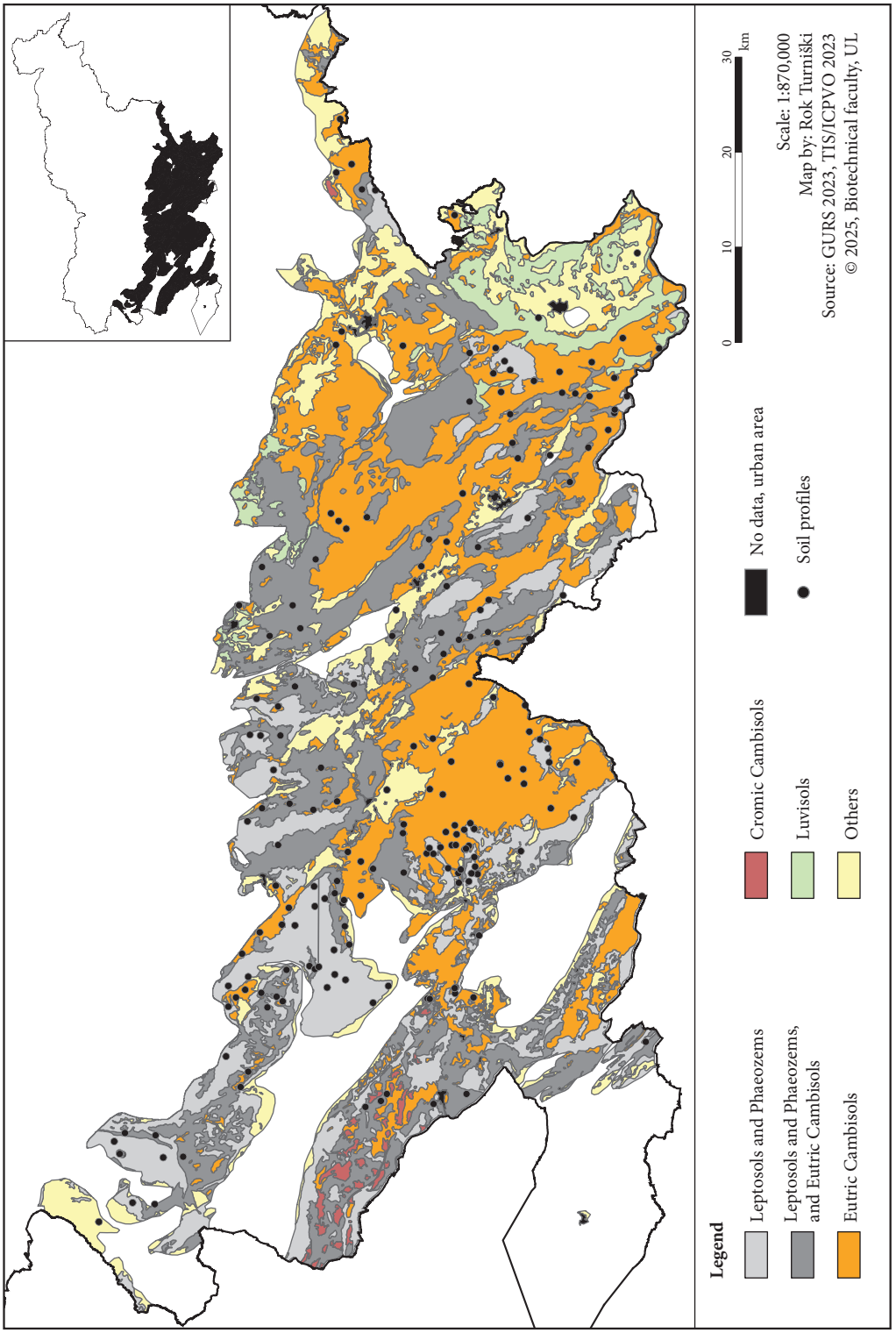
3 Results

On limestones and dolomites the main soil groups are Leptosols and Phaeozems (slv. *rendzina*) (42.7%), followed by Eutric Cambisols (slv. *rjava pokarbonatna tla*) (36.3%), Luvisols (slv. *izprana tla*) (6.7%), Rhodic

Table 1: Overview of analysed soil properties.

Variable	Description	Unit	Method
pH	Soil acidity	–	SIST ISO 10390: 2005: Soil quality – Determination of pH
Sand	Sand content	%	SIST ISO 11277: 2009: Determination of Particle Size Distribution in Mineral Soil Material. Method by Sieving and Sedimentation.
Silt	Silt content	%	
Clay	Clay content	%	
SOM	Soil organic matter	%	SIST ISO 14235: 1999: Soil quality – Determination of organic carbon by sulfochromic oxidation.
N	Total nitrogen	%	SIST ISO 11261: Soil quality – Determination of total nitrogen – Modified Kjeldahl method.
CN	Carbon-to-Nitrogen ratio	–	Calculated
CEC	Cation exchange capacity	$cmol_c\ kg^{-1}$	Burt 1992
Ca-sat	Calcium saturation	%	Calculated
Mg-sat	Magnesium saturation	%	Calculated
BS	Base saturation	%	Calculated
P_2O_5	Plant-available phosphorus	$mg\ kg^{-1}$	SIST-TS: Method AL (Egnér et al. 1960)
K_2O	Plant-available potassium	$mg\ kg^{-1}$	SIST-TS: Method AL (Egnér et al. 1960)

Figure 1: Soil map of the Dinaric karst of Slovenia 1:250,000 (modified) with locations of the analysed soil profiles. ► p. 25


Legend
Leptosols and Phaeozems
Leptosols and Phaeozems, and Eutric Cambisols
Eutric Cambisols
Cromic Cambisols
Luvisols
Others
No data, urban area
Soil profiles
0
10
20
30
km
Scale: 1:870,000
Map by: Rok Turniški
Source: GURS 2023, TIS/ICPVO 2023
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Cambisols (slv. *rdečerjava tla*) (0.7%) and Nudilithic Leptosols (slv. *litosol*) (0.6%), which together account for 87% of all soils in the area (Figures 1 and 2, Table 2). Alternating with limestones and dolomites, various clastic consolidated or unconsolidated sedimentary rocks, such as Pleistocene (Markič 2009) and Pliocene (Bavec and Pohar 2009) sediments are also found, especially in alluvial plains and karst poljes, where different soil types have developed. The most common are Eutric Cambisols (slv. *rjava tla, evtrična*) (7.1%) and Dystric Cambisols (slv. *rjava tla, distrična*) (1.5%), followed by Gleysols (slv. *oglejena tla*) (1.4%), and Fluvisols (slv. *obrečna tla*) (0.7%). In the Lower Carniola, in the area of Novo mesto, Eutric Cambisols have developed on Pleistocene and Pliocene unconsolidated sediments, as well as on marlstones and marl sediments. Eutric Cambisols have also developed on karstic alluvial plains covered with clayey alluvial sediments, and on gravel deposits, and moraines. Hydromorphic soils are associated with a high water table. Gleysols (1.4%) occur on alluvial plains, while Stagnosols (0.4%) are more common on slopes. The combination of calcareous and non-calcareous rocks is also common. In the south of the Ljubljana region, dolomites alternate with siliceous shales, clays, siltstones and sandstones. Dystric Cambisols have developed on siliceous clastic sedimentary rocks. The characteristics of the most common soil groups developed on limestone and dolomite are presented in Table 2 and Figures 3 and 4.

Leptosols and Phaeozems are generally the shallowest soils. Their total profile depths varies from very shallow (a few cm) to about 60 cm. Rendzinas mostly have a silty to silty-clayey texture. They are rich in organic matter, especially in the Oa and Ah horizons (average C_{org} contents of 30% and 13%, respectively). Soils are mostly slightly acidic, with an average value of 6.3. The lowest pH values occur in Oa and Ah horizons. Leptosols and Phaeozems are eutric, with high average base saturation value of 75.8%. CEC values are high, with an average of 49 $cmol_c\ kg^{-1}$ soil. The content of plant-available phosphorus (P_2O_5) and potassium (K_2O) is low, with an average value of 62 mg $P_2O_5\ kg^{-1}$ and 155 mg $K_2O\ kg^{-1}$. The highest concentrations occurring in the O horizons, with an average values of 147 mg $P_2O_5\ kg^{-1}$ and 176 mg $P_2O_5\ kg^{-1}$, due to biocycling.

Eutric Cambisols differ in soil depth, generally ranging from 30 cm to 200 cm. The texture classes of Eutric Cambisols are mostly loam, silty clay loam, clay loam, and clay. Topsoils have the highest concentration of organic matter, especially Oa and Ah horizons (averages of 47% and 21.7%, respectively). Higher organic matter content is also characteristic of A (average 7.1%) and Ap (average 6.2%) horizons. The average CN ratio is 11. Organic matter content and CN ratio decreases with soil depth (Figure 4). Eutric Cambisols are in average moderately acidic with an average pH value of 5.7. The upper parts of soil profiles, rich with organic matter, are usually more acidic than the lower parts. Higher values in the lower BC horizons are a consequence of the contact with the carbonate parent material. Typical Eutric Cambisols have an average base saturation of 71%, whereas leached varieties show lower values, with an average of 48%. CEC values are relatively high, with an average value of 30 $cmol_c\ kg^{-1}$ soil. Similar to Leptopsols and Phaeozems the supply of available phosphorus and potassium in soils is low, with avarages 55 mg $P_2O_5\ kg^{-1}$ and 129 mg $K_2O\ kg^{-1}$. The higher contents of phosphorus and potassium are characteristic for Oa, Ah, and Ap horizons. In Oa and Ah horizons, high values (an average > 95 mg $P_2O_5\ kg^{-1}$ and > 200 mg $K_2O\ kg^{-1}$) result from biorecycling, while Ap horizons show the apparent influence of fertilizing (an average of 97 mg $P_2O_5\ kg^{-1}$ and 410 mg $K_2O\ kg^{-1}$).

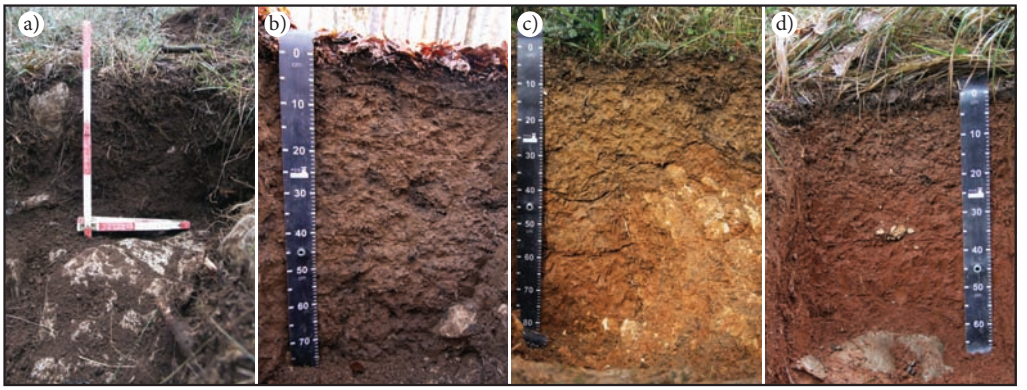
In some areas, mainly on the Karst Plateau, **Rhodic Cambisols** also occur, representing typical Mediterranean soils (Figure 2d). Similar to Eutric Cambisols, Rhodic Cambisols vary in soil depth. In concave geomorphological settings, like dolines, they are several metres thick. Generally, they are clay rich, with texture classes of silty clay loam, clay loam and clay. The SOM content is lower compared to Eutric Cambisols, with an average of 2.6%. The average CN of the soil is 11. Soils are moderately acidic. The average pH value (5.2) is lower compared to Eutric Cambisols, which also reflects in lower base saturation. Base saturation is the highest in the A (average 56.5%) and Ap horizons (average 83.1%), while the cambic Brz (rz comes from Latin residuum) and illuvial Bt horizons are more depleted, with an average value of 51.5%. E horizons in leached Rhodic Cambisols are dystric, which is also common in Bt. Similar to Eutric Cambisols, CEC values are relatively high, with an average of 32.2 $cmol_c\ kg^{-1}$ soil.

Luvisols are well-developed soils (Figure 2c), usually deeper than 70 cm. Their diagnostic feature is a pronounced texture differentiation between the upper (A, E) and lower (Bt) horizons. In the E horizon, which lies directly above the Bt horizon, the average clay content is 29.7%, and in the Bt horizon, 46.5%. In general, the A, E, and Bt horizons contain little sand (median < 12.6%) (Figure 3). SOM content decreases with depth; the topsoil under forest vegetation is rich in organic matter (the average SOM content in Oa/Ah

is 28%). The eluvial and illuvial horizons contain less than 2.5% SOM. The average pH value (5.2) is similar to Rhodic Cambisols, however the range is broader (2.9 to 6.9). Except for Oa/Ah and A horizons, the lowest pH values were detected in E horizons (average 4.6). The average pH value in Bt horizon is 5. The lower values of base saturation are noticeable in E horizons (32.7%), while values in Bt are higher (51.5%) (Table 3). The average CEC value is 27.6 $cmol_c\ kg^{-1}$. The supply of available phosphorus and potassium is very low, with average concentrations of 50 $mg\ kg^{-1}$ and 112 $mg\ kg^{-1}$, respectively.

Table 2: Properties of predominant soil groups in the Dinaric karst of Slovenia. For selected chemical soil properties, averages and ranges (in brackets) are presented. The area was calculated according to the Soil Map of Slovenia 1:25,000 (Infrastrukturni . . . 2023). The »/« symbol is not a classification rule but replaces the word »or«.

	Leptosols and Phaeozems	Eutric Cambisols	Luvisols	Rhodic Cambisols
Area (km^2)	2317.4	1970.2	362.1	30,7
Area (%)	42.7	36.3	6.7	0.7
Predominant lithology	limestone and dolomite			
Predominant natural vegetation	*Omphalodo-Fagetum, Lamio orvalae-Fagetum, Ostryo carpinifoliae-Quercetum pubescentis* (Karst Plateau)			*Ostryo carpinifoliae-Quercetum pubescentis*
Predominant land use	Forest			Forest/agricultural
n (soil profiles)	92	116	41	8
n (soil horizons)	183	375	163	26
Typical profile	Oa-C/R, Ah-C/R, A/Ap-C/R	Oa/Ah-A-B-C/R, Ah-B-C/R, A/Ap-B-C/R	Oa/Ah-E-B-C/R A/Ap-E-Bt-C/R	Oa/Ah-A-B-C/R, Oa/Ah-E-B-C/R, Ah/Ap-B-C/R
Typical depth (cm)	0–30	30–100	70–125	30–150
Typical texture	silty	silty to clayey	silty to clayey	clayey
pH	6.3 (3.6–7.4)	5.7 (3.6–7.6)	5.7 (3.6–7.6)	5.2 (3.7–7.2)
SOM (%)	16.2 (1.4–83.3)	6.4 (0.2–71.8)	6.9 (0.31–70.8)	4.5 (0.6–12.3)
N	0.58 (0.06–2.25)	0.40 (0.04–14.6)	0.60 (0.04–14)	0.22 (0.07–0.53)
CN	15.7 (9–40)	13.1 (1–38)	14.5 (1–100)	10.8 (5–16)
CEC ($cmol_c\ kg^{-1}$)	48.9 (21–124)	30.3 (10.7–76)	27.6 (13.4–99.9)	32.2 (16.7–45.9)
Base saturation (%)	75.8 (27.2–99.5)	63.5 (5.6–96.7)	42.9 (2.4–84.4)	54.2 (5.5–89.5)



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Figure 2: Main soil types formed on limestones of the Dinaric karst a) Leptosol, b) Eutric Cambisol, c) Luvisol, and d) Rhodic Cambisol.

The comparison of soils developed on limestone and dolomite revealed clear differences in Ca and Mg saturation, reflecting the contrasting mineral composition of the parent material. Soils developed on limestone exhibit higher Ca saturation, whereas those formed on dolomite show markedly higher Mg saturation (Figure 5). However, no significant differences were observed in the other soil properties.

Forests cover as much as 72.5% of the area of the Dinaric karst (Ministry … 2021). Permanent grassland (15.5%) is the second most common type of land use in the area, while arable land and combined land use (i.e., agroforestry) lag behind with 2.3% and 1.3%, respectively. Land use affects some properties of the horizons, so in Table 3 we present mean values and ranges for the horizons according to forest (F) and agricultural (A) land use.

Forests promote the accumulation of organic matter in their uppermost organic horizons (Oi, Oe, Oa), with a high organic matter content in the Oa horizons (> 28.9%). The organic surface layers also show high CN ratios – on average 20.7, 19.9 and 26.9 in Leptosols/Phaeozems, Cambisols and Luvisols, respectively (Table 3). The high organic matter content is also reflected in a very high cation exchange capacity. The average CEC in the Oa/Ah horizons of the forest soils is 68.6, 52.5 and 51.5 $cmol_c\ kg^{-1}$ in Leptosols/Phaeozems, Cambisols and Luvisols, respectively. Forest soils typically exhibit lower pH values in the upper horizons than agricultural soils.

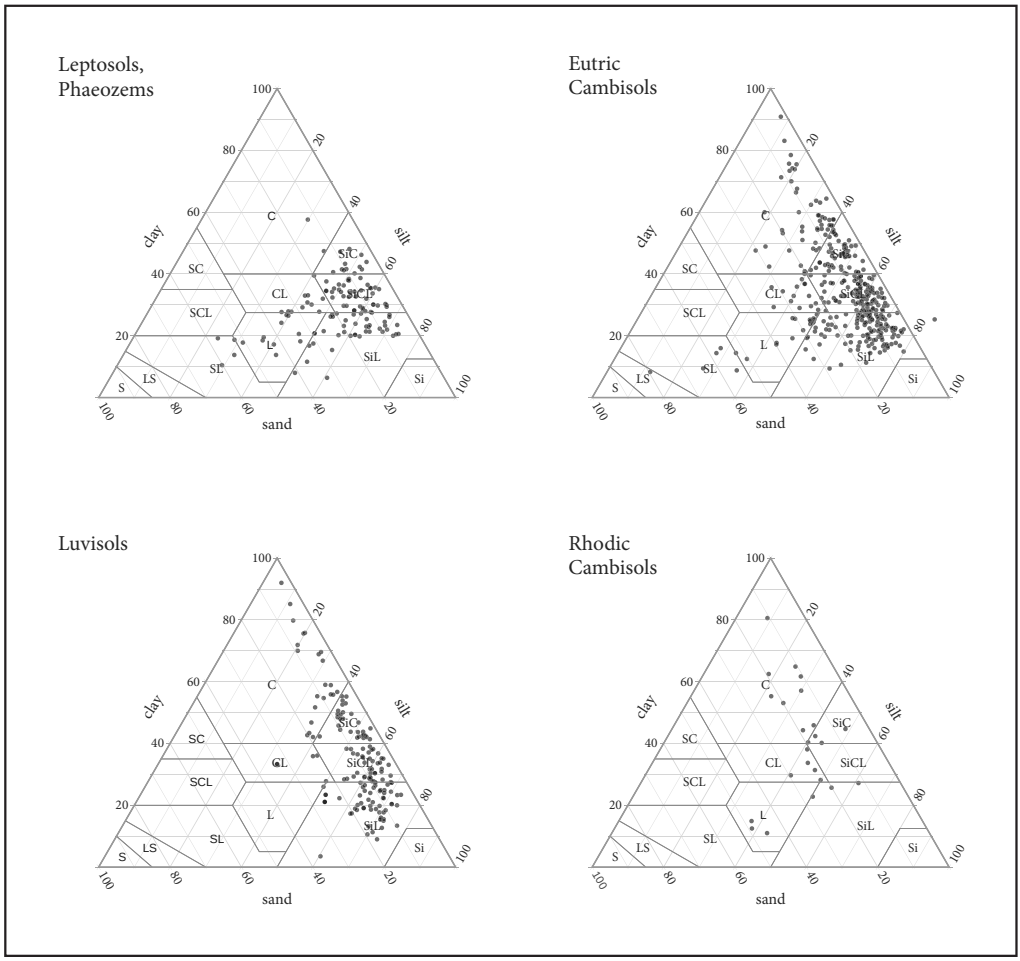


Figure 3: Soil texture of Leptosols and Phaeozems, Eutric Cambisols, Luvisols, and Rhodic Cambisols.

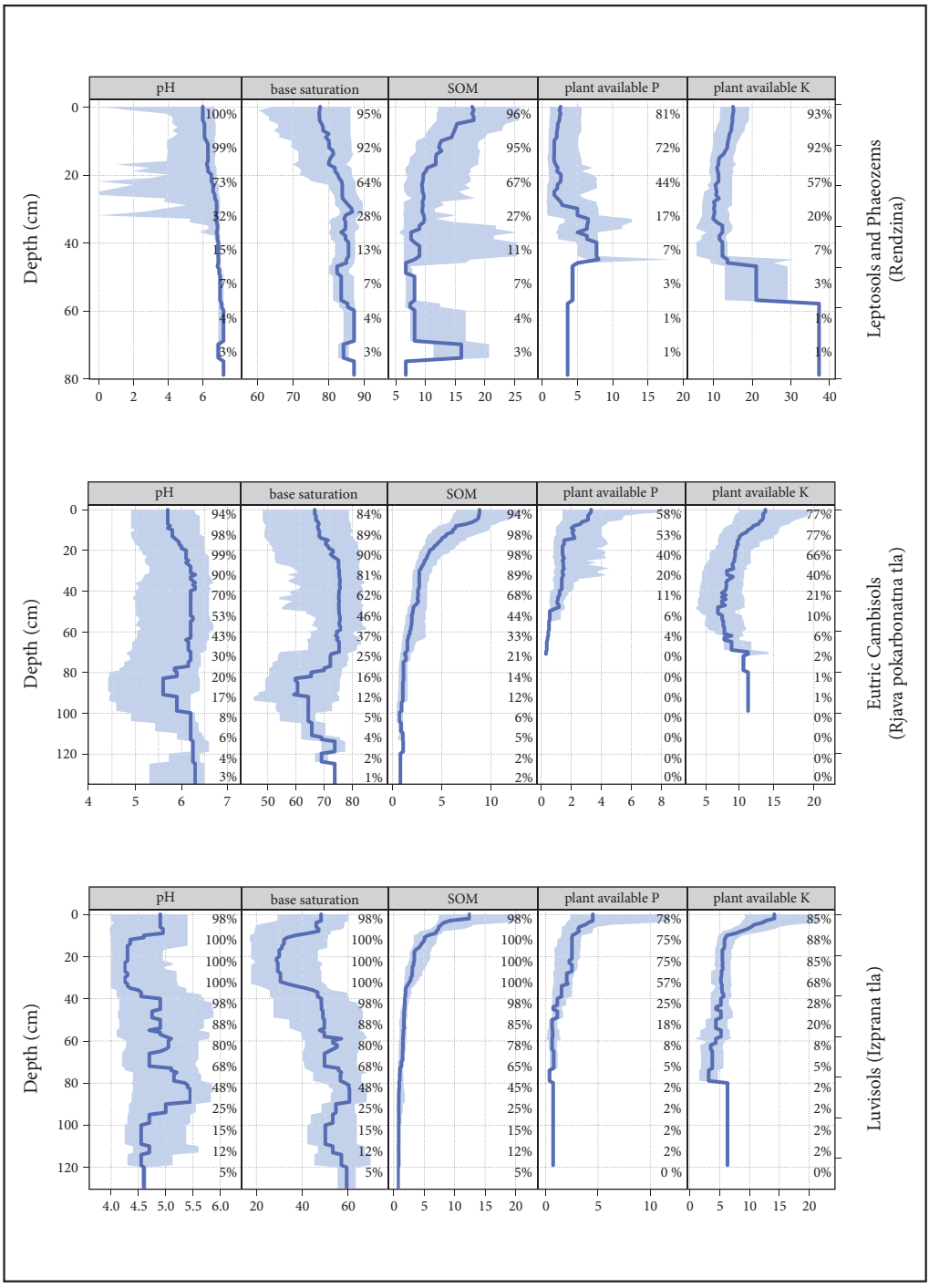


Figure 4: pH, base saturation (%), SOM (%), plant available phosphorus (mg kg^{-1}) and plant available potassium (mg kg^{-1}). The solid blue lines represent the median that is bounded by the 25th and 75th percentiles. The percentages along the right side of the depth axis describe the fraction of profiles that contributed to the computations.

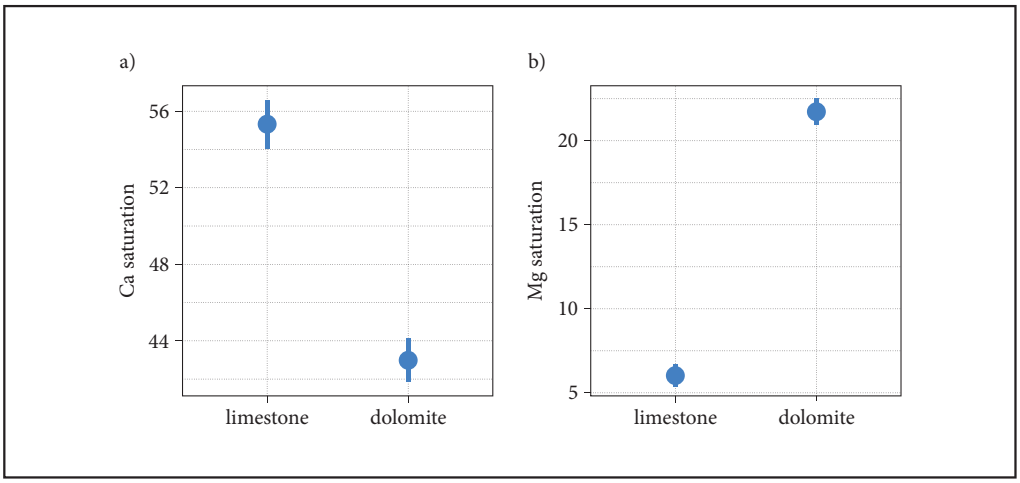


Figure 5: Mean values with standard errors for Ca saturation and Mg saturation in soils developed on limestone (n = 230) and dolomite (n = 139) in the Dinaric karst region.

4 Discussion

4.1 Pedogenesis on limestone and dolomite

The diversity of soils on limestone and dolomite is closely related to karst geomorphology (Stritar 1990; Turniški 2024). The main pedogenetic processes involved in soil development on carbonate rocks are organic matter accumulation, carbonate dissolution and leaching, and clay illuviation (Birkeland 1999). Soils begin to develop with the accumulation of organic matter when bare rock is covered by pioneer vegetation (Blume et al. 2016). Protection from erosion simultaneously promotes the accumulation of mineral weathering products. In the early stages, however, only a thin horizon with a high organic matter content can be recognised. These soils are classified as Nudilithic Leptosols. The organic matter is poorly decomposed (CN ratio > 25), especially at higher altitudes. Nudilithic Leptosols occur locally on very steep slopes where intense erosion processes prevent the accumulation of soil material.

As the humus accumulative horizon thickens, Leptosols and Phaeozems, the most common soil types in Slovenia's Dinaric karst, begin to develop. They are characterized by shallow profiles, consisting of only O and/or A horizons overlying the parent material. The contact with parent material influences soil pH and base saturation; both parameters are higher compared to more developed soil types, Cambisols and Luvisols. Due to their high organic matter content, the CEC is high, although the clay content is lower compared to Cambisols and Luvisols (Table 2, Figure 3). Leptosols and Phaeozems vary in thickness, content of organic matter, and the rate of organic matter decomposition. Organic matter accumulation is largely dependent on climatic conditions (Suhadolc and Črepinšek 2018). At higher altitudes, i.e., on the Snežnik Plateau, the Trnovo Forest Plateau (slv. *Trnovski gozd*), Mount Gotenica, the organogenic form of Leptosols and Phaeozems is common. This form can also be found in cold micro-locations at lower altitudes, especially on northern slopes. However, pure organogenic forms of Leptosols are rare, mainly occurring above 900 m.a.s.l. While closely associated with organo-mineral forms of Leptosols and Phaeozems, these soils tend to frequently alternate with Nudilithic Leptosols at higher altitudes. The most widespread forms of Leptosols and Phaeozems are organo-mineral soils with mull humus (Figure 2a), characterized by the accumulation and gradual mineralization of organic matter as their main soil-forming processes (Stepančič and Ažnik 1976). Predominantly they are found on limestone and dolomite, often in combination with more developed soil types, i.e., Eutric Cambisols; to a lesser extent, they are also present on carbonate gravels, moraines, and alluvial river deposits on karst poljes. A thin Brz horizon can sometimes be observed

Table 3: Chemical properties of the soil horizons within three main soil types of the Slovenian Dinaric karst. Data are shown for generalised horizons subdivided according to land use (A – agriculture, F – forest). Both mean values and ranges (in brackets) are presented.

Soil type	Soil horizon	Land use	pH –	SOM %	CN –	CEC $cmol_c\ kg^{-1}$	BS %
Leptosols and Phaeozems (slv. *rendzina*)	Oa/Ah	A	6.2 (5–7)	21.4 (15.3–30.3)	14.7 (11.2–20.2)	52.9 (43.4–74)	73.6 (48.3–89.8)
		F	6.0 (3.6–7.2)	30.5 (16.3–39.6)	20.7 (12.7–39.6)	68.6 (32.7–124)	73.4 (36.1–99.5)
	A	A	6.3 (4.8–7.4)	9.5 (2.2–14.9)	12.9 (9.4–20.9)	37.7 (24.6–58.1)	76.1 (49.2–91)
		F	6.4 (3.9–7.4)	9.3 (1.4–14.9)	16.2 (9.4–39.5)	43.2 (20.9–71.7)	75.1 (27.2–95.1)
	Ap	A	7.1 (7.0–7.2)	8.9 (3–8.6)	11.6 (9.2–15.1)	36 (29.3–39.5)	89.5 (86.5–91.6)
		F	–	–	–	–	–
Eutric Cambisols (slv. *rj. pokarbonatna tla*)	Oa/Ah	A	6.7 (6.4–7)	23.4 (16.8–30.6)	14.4 (11.1–17)	60.8 (44.2–76)	80.8 (75.8–87.2)
		F	5.2 (3.9–6.9)	28.9 (15.1–71.8)	19.9 (3.9–29.4)	52.5 (27.8–72.1)	54.2 (30.3–86.3)
	A	A	5.8 (4–7.6)	6.3 (1.3–13.2)	12 (1–19.8)	29.9 (16.3–61.3)	63.2 (12–93.9)
		F	5.5 (3.6–7.3)	7.6 (1.8–14.2)	16.8 (6.7–38.1)	31.9 (14.6–52.7)	61.4 (7.7–96.4)
	Ap	A	6.1 (5.2–6.9)	4.9 (2.6–10.8)	10.1 (6.7–14.9)	23.8 (13.9–35.7)	68.5 (38.3–87.4)
		F	–	–	–	–	–
	B	A	5.9 (3.8–7.6)	2.1 (0.2–10)	9.6 (1–18.7)	24.8 (10.7–46.7)	66.2 (17–96.7)
		F	5.5 (3.7–7.2)	3.2 (0.3–10.7)	13.9 (2.5–26.7)	29.1 (14.2–44.9)	63.1 (5.6–90.2)
Luvisols (slv. *izprana tla*)	Oa/Ah	A	–	–	–	–	–
		F	4.3 (2.9–6.5)	33.7 (15.4–70.8)	26.9 (15.5–100)	51.5 (41.6–99.9)	39.2 (15.3–71.7)
	A	A	5.5 (3.8–6.6)	8.1 (4.4–13.3)	12.4 (0.3–16.3)	27.8 (22.2–37.2)	54.2 (15.9–80.9)
		F	4.7 (3.3–6.8)	7.1 (3.2–12.7)	18.1 (14.1–24.6)	26.4 (17.3–36)	35.6 (6.5–83.5)
	Ap	A	4.7 (4.3–5.1)	5.9 (3.3–7.2)	11.8 (10.1–14.3)	24.3 (18.2–27.5)	33.9 (29.2–39.7)
		F	–	–	–	–	–
	E	A	5.1 (3.9–6.5)	2.8 (0.8–6.4)	9.3 (1–18.7)	19.6 (15.2–28.9)	45.9 (19.6–73)
		F	4.2 (3–6.5)	3.7 (0.7–9.9)	15.6 (5.4–28.3)	22.0 (13.4–43.1)	24.9 (3.8–70.4)
	Bt	A	5.1 (4–6.7)	1.3 (0.5–3.1)	8.4 (1–13.7)	24.3 (14.8–40)	53.9 (20–84.4)
		F	4.9 (3.8–6.9)	2.1 (0.3–5.4)	11.9 (2.6–19.8)	27.2 (13.9–46.8)	50.3 (2.4–82.8)

between A horizon and the underlying parent material, indicating further soil evolution. Such a transitional soil type, mainly found on less steep slopes or in limestone pockets and fissures, is named brown rendzina (Prus et al. 2015). The soil surface of Leptosols and Phaeozems on limestone is usually rocky, which gives a characteristic appearance to the karst landscape (Gams 2004). Most of the evaluated soils of this type also contain skeletal or rock debris. In contrast to the rendzinas on limestone, the rendzinas on dolomite can be found on unweathered rock and loose dolomitic sands. Due to the specific weathering of dolomite (Zupan Hajna 2014), these soils do not exhibit surface rockiness; nevertheless, they often contain coarse fragments within the soil matrix.

Eutric Cambisols are characterized by the presence of a cambic horizon (Brz), which is thought to have initially formed by the accumulation of insoluble residue of limestone and dolomite (Figure 2b; Vidic et al. 2015). However, following the advances in the development of pedogenetical models for this soil type (Duchaufour 1982), Stepančič and Lobnik (1985) described these soils as relict and undergoing polycyclic genesis. Additions of different allochthonous material (i.e., interbedded material, paleosoils, eolian dust), as well as polycyclic genesis were further discussed in investigations of Zupančič et al. (2018) and Turniški et al. (2023). Throughout the geological periods, soil material was translocated and resedimented, covering dolines, terraces and plateaus in some places with a blanket several meters thick. Often, we can find relict Brz horizons remaining in the subcutaneous channels and scallops of the chemically weathered bedrock and in larger depressions between the plateaus, where water erosion failed to remove them completely (Stepančič and Lobnik 1985). Pedogenetic processess, i.e., decarbonation and eluvial-illuvial processes, result in lower pH and base saturation in comparison with Leptosols and Phaeozems (Table 2). The Slovenian soil classification recognizes two subtypes: typical and leached (illuvial, luvic). The differences between the two are reflected in additional differentiation of soil material. Typical Eutric Cambisols show no apparent signs of eluviation, while the illuvial subtype shows textural differentiation in the profile; higher clay content in lower part of the profile and lower pH and base saturation in the upper part of the profile (Figure 3). The skeletal content in the soil differs depending on the parent material; Eutric Cambisols on limestone contain individual rounded rock fragments, while those on dolomite have a higher content of smaller and sharp-edged rock fragments. Eutric Cambisols occur throughout the Dinaric karst, most often on flats and at the middle altitudes on less steep slopes within the pockets and fissures in the local bedrock, alternating with Leptosols and Phaeozems. In such instances, the depth of the soil varies greatly within short distances and surface rockiness is very common (Ciglič et al. 2012).

Among Cambisols developed on limestone and dolomite, a distinct subgroup is represented by Rhodic Cambisols. These soils, known also as Terra rossa, are characterized by a reddish colour (5YR to 10R), which serves as an important diagnostic feature. It reflects the intensity of rubification, i.e., the preferential formation of hematite over goethite, which takes place in a Mediterranean climate (Schwertmann et al. 1982). The dominant theory of its genesis explains Terra rossa as a relict polycyclic soil, initially formed by the weathering of limestones in warm, dry climate conditions, resulting in clayey material rich in iron and aluminium oxides (insoluble residue) (Durn et al. 2023; Torrent et al. 2023). During the Pleistocene, the material was exposed to strong water and wind erosion, so it has been preserved mainly in caves, dolines and pockets, and fissures within the weathered bedrock (Stepančič 1978). However, the origin of the red residues and the evolution of this soil type are still debated (Liu et al. 2013). In Slovenia two subtypes of Rhodic Cambisols are known: »*kremenica*« (from Slovenian *kremen*, quartz) and »*ilovka*« (from Slovenian *ilovica*, clay) (Sušin 1964). The presence of chert skeleton in the soil determines the »*kremenica*« subtype, which forms on the Upper Cretaceous limestone containing chert nodules and sheets (Jurkovšek et al. 2013). The other form is »*ilovka*«, a clayey soil with or without a low chert skeleton content. Due to the presence of chert skeleton, »*kremenica*« has a higher sand content (average 21.6%) compared to »*ilovka*« (average 14.1%). The Rhodic Cambisols generally show evidence of illuvial processes.

In environments with higher precipitation rates, eluvial-illuvial processes play an important role in pedogenesis. The most evident process is the vertical translocation of clay, leading to the formation of an argic horizon. Luvisols are mainly found on plains protected from erosion and colluvial processes (Turniški and Grčman 2018). However, when they form in pockets and fissures on steeper slopes, Luvisols can also alternate with Eutric Cambisols, Leptosols and Phaeozems (Turniški 2024). Many Luvisols are also found on the Pliocene and Pleistocene sediments in the White Carniola (Turniški and Grčman 2018). In general, Luvisols consist mainly of clay and silty particles (Turniški and Grčman 2018). The average ratio of

clay in the illuvial horizon (Bt1) to that of the coarser-textured eluvial horizon is 1.6. Due to eluviation, Luvisols have lower average pH (4.7) and base saturation values (42.9%) compared to Leptosols, Phaeozems and Eutric Cambisols (Table 2). In general, Luvisols are poor in base cations. Due to their leaching into the lower horizons, the upper part of the Luvisols is usually dystric (base saturation < 50%). Higher values in the Bt horizons (Figure 4, Table 3) result from the accumulation of base cations and/or the influence of the carbonate parent material (Turniški et al. 2023). In some cases, higher concentrations of base cations in Oa/Ah and A horizons are due to biocycling (Čirič 1984). Sudden textural changes between the upper and lower horizons in some soil profiles indicate the presence of two-layered soils (Turniški et al. 2023), which are probably due to the aforementioned geological processes of material displacement during the Pleistocene. Distinguishing between originally related parent materials is challenging, but Turniški et al. (2023) suggested using element ratios to indicate different sources of soil material. The geochemical composition of the parent material is reflected in soil properties, as clearly evidenced by the differences in the proportions of Ca and Mg on the soil exchange complex between soils developed on limestone and dolomite. Since Ca plays a key role in the formation and stability of soil structural aggregates, differences in morphological characteristics could also be expected. However, such differences could not be evaluated within the framework of the soil map database.

4.2 Land use and human impact on soil properties

The favourable chemical properties of the soils on limestone and dolomite (Table 2) indicate their fertility and provide a solid basis for agriculture. The high cation exchange capacity (Table 2) reflects the high organic matter content in the O and A horizons and the high clay content in the B horizons. Both properties enable good retention of nutrients and water. The high content of base cations, i.e., calcium, magnesium and potassium, adsorbed on the soil colloids serves as a source of important plant nutrients (Weil and Brady 2017). A stable polyhedral soil structure allows water to percolate through the soil, which means that water stagnation rarely occurs in the soils despite the high clay and silt content. However, the initial neutral pH decreases in the subsequent stages of soil development due to the dissolution of carbonates and leaching (Turniški et al. 2023; see Table 2). This acidification would most likely have been buffered in cultivated areas through liming with carbonate-containing materials, which would have increased the pH value in the soil.

A large part of the Dinaric karst area has been classified as areas with natural or other specific constraints relevant for agricultural land use. This was demonstrated by additional soil surveys, mapping and soil analyses (Prus et al. 2017). The three main limitations to agricultural land use in the region are the shallow depth of the soils, their stoniness, and the karst geomorphology (Ciglič et al. 2012; see Figures 6a and 6b). Deeper soils only occur in alluvial plains and flats, in smaller and larger depressions such as dolines, poljes, and uvalas, and in subcutaneous cracks, channels, and scallops (Slabe and Hong 2009). Such karst forms act as traps for both aeolian (Sauro et al. 2009; Zupančič et al. 2018) and colluvial material (Gaiffe and Bruckert 1985), leading to the development of deep soils. For example, soils in dolines are often thicker with relatively silty upper horizons (Turniški 2024) and such soils provide favourable conditions for potential cultivation. Historically, some of these dolines were adapted for cultivation, also in the case of semicovered karst (Gams and Gabrovec 1999). The bottoms of dolines were levelled, and in some cases, additional soil material from the surroundings was added, creating a surface suitable for ploughing. In such cases, the properties of the original soils were altered, most notably in terms of soil depth. However, due to the limitations in the available data, it was not possible to assess systematic differences in the physical and chemical properties of these soils.

The vast majority of Leptosols and Phaeozems are covered by forest. The high proportion of stones and boulders on the surface of these soils generally prevents large-scale clearing or mowing and limits land use mainly to grazing. However, mowing is possible only in areas where stones have been systematically removed or where their presence on the soil surface is negligible. The few arable areas in the region are mainly associated with Eutric Cambisols or Luvisols. The relationship between soil properties and land use is a dynamic, two-way system (Verheyen et al. 2001). Agricultural land use alters the properties of the topsoil and influences various pedogenetic processes in the soil (see Table 3 and Figure 7). As shown in Figure 7, there are differences in pH, base saturation, CEC and organic matter content between forest and agricultural soils. In particular, the agricultural topsoils have a higher pH and base saturation than



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Figure 6: a, b) shallow soil with subsurface rockiness (hidden rockiness) and distinct epikarst forms, c) typical karst landscape with agricultural terraces on dolomite.

the forestry topsoils, with values of 5.9 and 65.7% compared to 5.5 and 59.3% (Figure 7). Conversely, organic matter content and CEC are lower in agricultural topsoils than in forest soils (Figure 7). This trend is expected as both ploughing and nitrogen fertilisation favour the mineralisation of organic matter, especially in the Oa and Ah horizons where organic matter is not stably bound to the mineral soil fraction (Blume et al. 2016). Agriculture also modifies the expression of eluvial-illuvial processes, with liming, fertilisation and ploughing obscuring the contrast between the eluvial E and illuvial Bt horizons (Table 3).

The use of fertilisers in the Dinaric karst region has not been intensive. As demonstrated in Figure 7, the content of plant-available phosphorous in the local topsoils remains low, on average less than 50 mg kg^{-1} soil, regardless of soil use. Phosphorous availability could be further reduced by its adsorption to iron oxides and aluminium hydroxides (Blume et al. 2016) (Figure 3). The content of plant-available potassium is naturally higher (140 mg kg^{-1}), originating from primary silicates and clay minerals. Further, the plant-available potassium content of agricultural topsoils is higher than that of forest soils. Rather than being associated with fertilisation, such high values are most likely correlated with the lower organic matter content and consequently higher mineral soil content of ploughed soils.

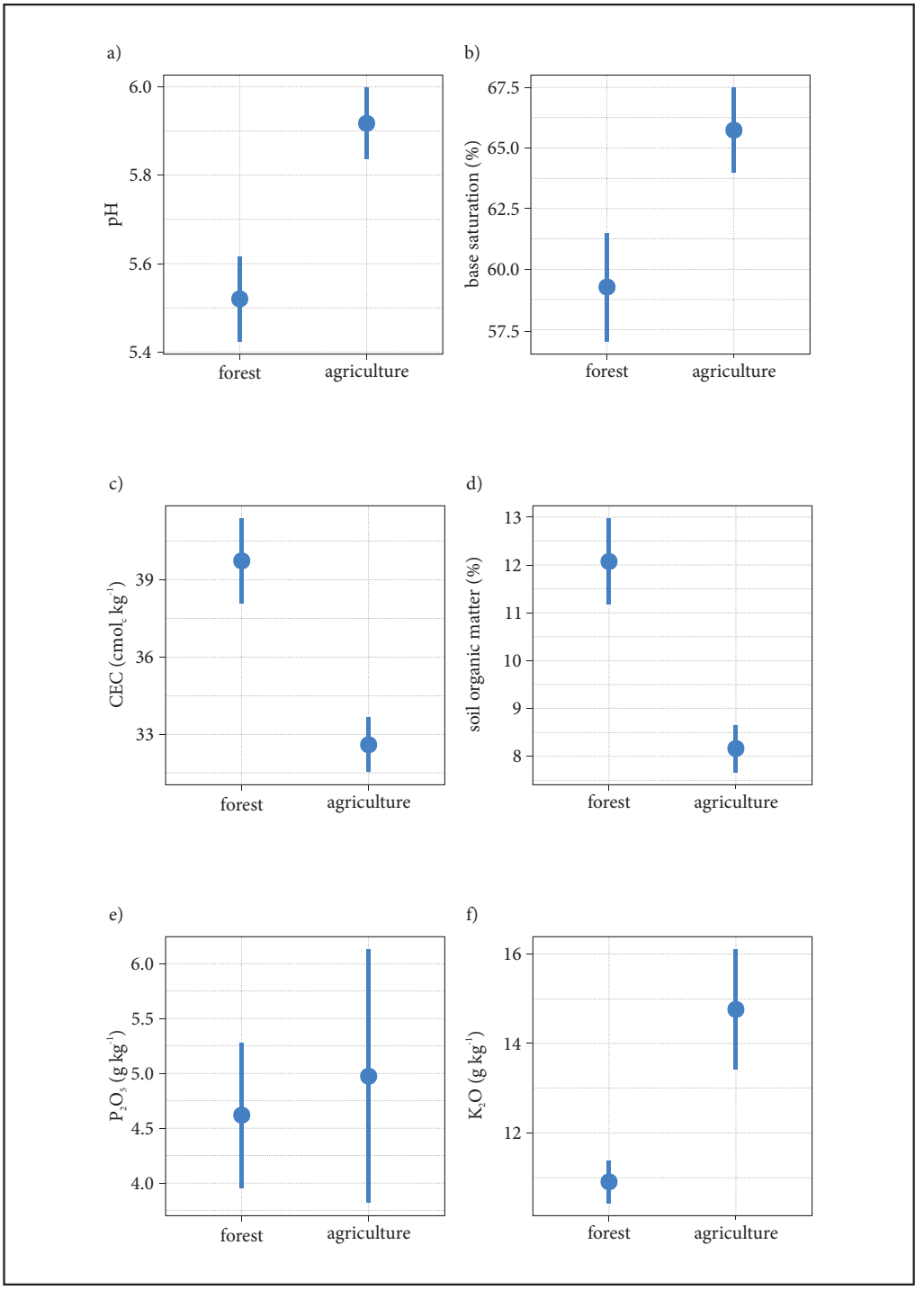


Figure 7: Mean values with standard errors for pH, base saturation, CEC, soil organic matter, plant-available phosphorous, and plant-available potassium in topsoils at 0–30 cm depth under forest (n = 131) and agricultural land (n = 121) in the Dinaric karst region.

5 Conclusion

The formation and development of soils is a complex spatio-temporal phenomenon involving various pedogenetic factors and processes. In the Dinaric karst region, the distinct chemical and physical weathering of limestone and dolomite affects the physiochemical properties of local soils. The variations in the depth and stoniness of the soils are mainly caused by the local sub-surface and surface topography, including variations in elevation, slope and exposure, which in turn influence the microclimate and the movement of water and soil masses on the slope. In places where mineral material accumulates, eluvial-illuvial processes are favoured under the influence of high precipitation, leading to the formation of argic horizons. The interplay of all these factors has contributed to the formation of the three predominant regional soil types: Leptosols and Phaeozems, Eutric Cambisols and Luvisols, which differ in their suitability for agriculture and other ecosystem services. A systematic review of the soil map database also revealed certain limitations in assessing the role of karst geomorphology in soil characteristics. To achieve a better understanding of these relationships, as well as to determine the extent and nature of anthropogenic influences on soil development, further research is required.

ACKNOWLEDGEMENT: This study was supported by the ARIS research program »Agroecosystems« (P4–0085) and the Infrastructure centre for soil and environmental protection (ARIS I0–0022–0481–06).

RESEARCH DATA: For information on the availability of research data related to the study, please visit the article webpage: https://doi.org/10.3986/AGS.14434.

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